Renewable and Sustainable Energy Reviews 16 (2012) 5466–5478

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Modeling and investigation of the wind resource in the gulf of Tunis, Tunisia

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ARTICLE INFO

Article history:
Received 5 September 2011
Received in revised form
29 April 2012
Accepted 3 May 2012
Available online 31 July 2012

Keywords:
Wind speed
Weibull distribution
Wind roses
Wind power density
Tunis

ABSTRACT

The development of wind energy conversion systems becomes one of the most important aims of many developing countries such as Tunisia. This is due to the reduction in wind turbine costs, and fossil fuel atmospheric pollution. The evaluation of wind power potential is necessary to estimate wind resource and therefore conduct the suitable decisions for the wind power generation projects, technical and economical feasibility. The presented work in this paper was to investigate the potential of wind resource in the Gulf of Tunis in Tunisia. The hourly mean wind speed and wind direction with a 10-min time step provided by the NRG (National Resources Group) weather station were used to analyze the wind speed characteristics and the wind power potential. Weibull parameters are estimated based on the most frequently used methods in which their accuracy was compared based on different goodness of fit tests. Those wind characteristics are required to give the picture of wind potential distribution in the Gulf of Tunis.

Contents

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http://dx.doi.org/10.1016/j.rser.2012.05.004

1. Introduction

Nowadays, the socio-economic development is one of the important goals of many countries. However, this goal is always accompanied by an increase of energy demand. Actually, this target has completely failed in many countries all over the world due to the lack of electrical energy production processes. Indeed, it is estimated that two billion citizens in developing countries suffer from lack of grid based electricity service [1]. Unfortunately, several applications with sensitive and strategic interest, for instance, the relays of telecommunication, border stations, isolated habitat, clinics, etc. require continuous and permanent energy supply. In some cases, grid extension can be impractical because of dispersed populations. Hence, small off-grid stand-alone renewable energy systems represent a significant solution for narrowing the electricity gap in rural parts of the developing world [2,3]. Judged as clean and abundantly available in nature, renewable energy sources like wind turbine (WT) and solar photovoltaic (PV) are now well developed and cost effective. Note that wind energy is an indirect form of solar energy, as the wind results from the fact that the Earth's equatorial regions collect more solar radiation than the polar regions, causing large-scale convection currents in the atmosphere [4]. Moreover, wind energy has a wide use and represents the fastest growing energy technology. Statistics have already shown that its yearly growth in terms of installed capacity is very promising [5].

Historically, since the first oil price shock, the main awareness was projected on wind energy because it is one of the most friendly and abundant renewable resources. Since the early 1970, wind energy has been improving and it becomes the most sustainable energy resources. The global wind energy industry has been rapidly re-emerging and many technological progresses have also significantly reduced the price of wind power. Certainly, in the last decade of the twentieth century wind technology was widely developed, its world-wide capacity was grown and a large number of wind turbines were commercially distributed.

It is important to state that more than 83% of the world-wide wind capacity is installed in only five countries: Germany, USA, Denmark, India and Spain where most of the wind energy knowledge is developed [6]. At the beginning of this century, the improvement of wind energy continued and it has been implicated in many fields like education, research and some expert projects for electric use.

The spread of wind energy progress is not evenly distributed around the world. By the end of 2001, the total operational wind power capacity worldwide was 23,270 MW. We note that 70.3% of this capacity was installed in Europe, followed by 19.1% in North America, 9.3% in Asia and the Pacific, 0.9% in the Middle East and Africa and 0.4% in South and Central America [6].

At the present time, wind turbines are the most modern technologies that can be installed quickly [7,8]. At the end of 2008, the established wind power capacity was around 159.2 GW for the whole world and only 593 MW in Africa but that is set to change rapidly thanks to new plans which were declared there. For example, Egypt has announced projects to have 7200 MW of wind electricity by near 2020, meeting 12% of the country's energy needs. Over the same period, Morocco aims to satisfy 15% of its electrical energy requirement based on wind energy farms. Unlikely, South Africa and Kenya have not announced such long-term goals and so forth.

Concerning Tunisia, the acceleration of the socioeconomic development has involved a strong growth in energy supply. During the 1994–1996 period, Tunisia has recorded its first energy balance deficit. After that a short surplus was restored. However, in 2001, the deficits appeared again as a result of increasing demand and stagnating supply. Historically, Tunisian energy consumption grew by 326% between 1971 and 2004 [9]. For the same period, the Tunisian energy production grew by only 38%. As Tunisia became a net energy importer and on following the increase in oil prices, Tunisia launched an energy conservation program during the 2005–2008 period. This program aims to reduce demand, improve investments in renewable energy and developments in the widespread use of natural gas. A second program was launched during the 2008–2011 period. This program aimed to decrease energy supply by 20%, entail energy conservation in all sectors of the economy, and develop the renewable energies in Tunisia. A strategic study on energy efficiency in Tunisia has proved that Tunisia can save 30 Mtoe by 2020 and 80 Mtoe by 2030 [10]. Tunisia also has a great potential in the field of renewable energy (e.g., solar and wind). The wind energy branch for power production represents the most important portion of this potential. Solar water heating is ranked second, followed by biogas [11]. A strategic study on the development of renewable energy in Tunisia showed that the penetration of renewable energies can exceed more than 11.7% by 2020 and 12.2% by 2030. Tunisia implanted its first wind farm in El-Haouaria region with an installed capacity of 55 MW [12]. After the start of the 190-MW wind power plant of Bizerte, Tunisia is now producing 244 MW (MW) from wind energy in 2012.

2. Wind energy assessment: An overview

In the last decade, wind characteristics and its power potential have been frequently analyzed. For instance, in Europe, recent studies were made by Akdag and Dinler [13], in Turkey, to develop a new method to estimate Weibull distribution parameters for wind energy applications. In the same place, another analysis concerning wind characteristics was elaborated by Ucar and Balousing [14] using the wind speed data collected from six meteorological stations from 2000 to 2006. In Greece, Fyrippis et al. [15] have investigated the wind power potential of Koronos village situated in the northeastern part of Naxos Island using real wind data by a measurement mast. In Hungary, Tar [16] has examinated the time series of monthly average wind speed in the period between 1991 and 2000 measured on seven Hungarian meteorological stations. In Italy, Ouammi et al. [17] have analyzed the monthly and seasonal variation of the wind characteristics in four meteorological stations in Liguria region, in Northwest of Italy using the wind speed data recorded between 2002 and 2008 at these stations.

Concerning Asia, Chang and Tu [18] have evaluated in Taiwan the monthly capacity factor of Vestas V47–660 kW turbines using chronological and probabilistic wind speed data. In Oman,

Albadi and El-Saadany [19] have formulated a new wind turbine capacity factor (CF) estimation using wind speed characteristics at any site and the power performance curve parameters of any pitch-regulated wind turbine. In Bahrain, Jowder [20] has analyzed the hourly measured wind speed data for years 2003–2005 at different hub heights to estimate the potential of wind power generation in this country. In Korea, Ko et al. [21] have investigated the availability of wind energy based on a wind data for 30 years from 1978 to 2007 provided by automated synoptic observation system (ASOS) of meteorological observatories. In Tehran, the wind characteristics of the Iranian capital have been analyzed by Keyhani et al. [22] using the statistical wind speed measurements of eleven years. In the state of Kuwait, the wind characteristics have been estimated by Al-Nassar et al. [23] using the measured wind data for all stations in Kuwait, from January 1998 to December 2002.

In the American continent, the wind technology has been improved; in fact, in the city of Triunfo in the state of Pernambuco in the northeast area of Brazil, wind potential has been assessed by de Araujo et al. [24] and a wind farm was simulated by using 850 kW wind turbines given a total of 20 MW installed using wind speed data measured by the SONDA (Sistema de Organização Nacional de Dados Ambientais) project's meteorological station during a period of time of 30 months. In Minnesota in the United States of America, Wichsera and Klinkb [25] have gathered the wind data in over 3 years and analyzed the wind power potential there. In the Waterloo region in Canada, Meishen and Xianguo [26] have investigated the wind characteristics and the wind energy potential in this region.

For the African continent, in Rwanda, Safari and Gasore [27] have evaluated the wind power characteristics in different locations in this country using time series of hourly measured wind speed and wind direction for the period between 1974 and 1993 on five main Rwandian meteorological stations. In Egypt, Ahmed Shata and Hanitsch [28] have evaluated the wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt using Wind data from 10 coastal meteorological stations. Recently Ahmed Shata [29] has also evaluated the wind characteristics in Ras Benas city located on the east coast of Red Sea using measured data and he has selected the suitable wind turbine for the considered site at different hub heights. In Algeria, Himri et al. [30] have also assessed the wind power potential at the stations of Adrar, Timimoun and Tindouf using wind speed data over a period of almost 10 years between 1977 and 1988 at these sites.

3. Wind energy status in Tunisia

This present study is related to the wind energy assessment in the central coast of the Gulf of the capital of Tunisia which represents an intriguing cross-cultural blend of Europe and Africa. It is located on the North African coast of the Mediterranean Sea, with 1298 km coastline, between Algeria and Libya and just south of Italy. Tunisian mainland is situated between the approximate latitudes 30–37°N and longitudes 8–12°E. This country has a small surface area of 163,210 km^2, an average population density of 56 persons and a maximum altitude of 1544 m (Jbal-Chaambi) [31].

The north of Tunisia has a wet climate while the desert (aridity) is spread out in the south with Saharan dry weather beginning from the state of Tataouin to the Libyan borders. In fact, the occurrence of hot southern winds, in spring and summer seasons, is responsible for the semi-arid weather in the south. The coasts are extensive from Tabarka to the island of Jerba and Zarzis. The hilly regions of Tunisia located in North-West and the West of Tunisia are characterized by little wind potential while the other regions of the country and specially the coastal plains are relatively windy.

Since 1980s, Tunisia formulated its national strategy in the field of new and renewable sources of energy [32]. At the beginning of the 21st century and especially when Tunisia has been considered one of the primary energy importer countries (2001), Tunisia has challenged a number of new renewable energy projects. In fact, the leading company for the electrical energy and Gas production in Tunisia (STEG) implanted the first wind farm in the northeast of the country with a total installed capacity achieving 20 MW. In the end of 2009, the total power installed reached a total capacity of 55 MW, which represents about 4% of the total electric power produced by STEG [33]. One of the main planned priorities of Tunisia is to achieve a share of 11% renewable energy sources primary supply by 2011 by installing new wind farms. Since the wind energy in Tunisia has not been studied thoroughly, several attempts have been made over the last ten years to analyze the wind potential in Tunisia. In this context, Elamouri and Ben Amara [34] suggested a study of 17 synoptic sites distributed on the entire territory of Tunisia. They have estimated the wind power potential and the wind speed characteristics at a height of 10 m above ground level based on the hourly wind data offered by the Meteorology National Institute. Ben Amar et al. [32] have studied the energy evaluation of the first wind farm section of Sidi Daoud. Dahmouni et al. [33] have analyzed the characteristics of wind energy in the Gulf of Tunis using a measurement of wind speed and wind direction at 20 and 30 m. They have evaluated the annual production of Enercon E82 at a height of 100 m above ground level.

In the present study, we treat 52,704 measurements of hourly mean wind speed and wind direction with a 10-min time step provided by the NRG weather station in the central coast of the Gulf of Tunis in Tunisia for the period 2008–2009. Further measurements, which were recorded every 10 min, could be provided by this station like ambient temperature and the solar flux. All the characteristics of wind energy of the studied site have been thoughtfully investigated and annually spatial mean information of wind energy potential has been presented (Fig. 1).

4. Modeling of wind potential characteristics

4.1. Wind speed adjustment

Wind speed data is frequently available from a different height than the hub height of the turbine. The effect of different heights on wind speed has been studied by many researchers [35,36]. Wind speed at any hub height can be adjusted from the measured wind

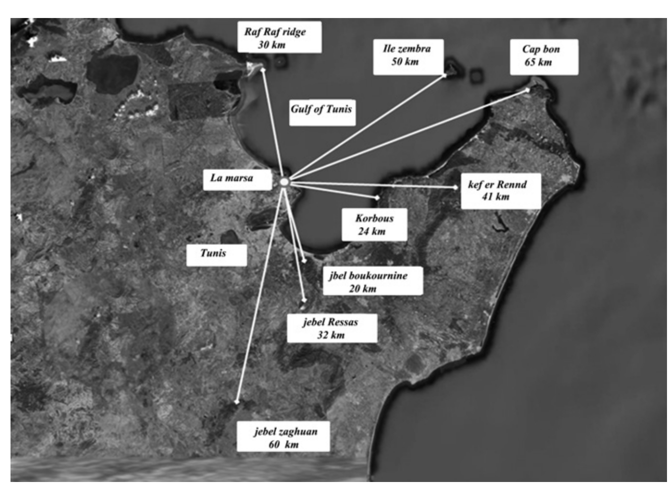

Fig. 1. Geographic position of the Gulf of Tunisia.

speed by anemometer using the power-law equation [37–42]:

$$\frac{V(Z_{hub})}{V(Z_{anem})} = \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \tag{1}$$

where Z_{hub}, Z_{anem}, α, $V(Z_{hub})$, $V(Z_{anem})$ are, respectively, the hub height of the wind turbine, the anemometer height, the power law exponent, the wind speed at the hub height of the wind turbine and the wind speed at anemometer height.

The exponent, α, under the heading "the ground surface friction coefficient", varies with ground level height, time of day, season, nature of the terrain, wind speeds, and temperature. A previous study was done by Dahmouni et al. [33] who indicated that the experimental value of the power law exponent is 0.185 and this value will be adopted in this work. Indeed, in this paper, we assume also that the air density is equal to 1.225 kg/m^3.

4.2. *Weibull distribution methods: an overview*

Wind speed frequency distribution has been represented by various probability density functions such as gamma, lognormal, three-parameter beta and Rayleigh, Weibull distributions. Recently, the Weibull distribution played central part in the study of wind climate and wind energy [43–58].

Since the Rayleigh distribution is only a subset of the weibull distribution, it has been one of the most commonly used and recommended distribution to evaluate wind energy potential and it has been used for commercial wind energy soft wares such as Wind Atlas Analysis and Application Program (WAsP) [59].

The Weibull distribution is often used to characterize wind regimes because it has been found to provide a good fit with measured wind data [60–64]. The probability density function is given as follows [65–77]:

$$f(V) = \frac{K}{C}\left(\frac{V}{C}\right)^{K-1} e^{[-(V/c)^{K}]} \tag{2}$$

where V, K and C are, respectively, the wind speed, the shape factor (unitless) and the scale parameter (m/s).

We note that the shape factor K value is an indication of the breadth of the wind speeds distribution. Sites with small K values correspond to broad distributions of wind speed, meaning that winds tend to vary over a large range of speeds and thus the power produced by the wind turbine would vary accordingly. Sites with large K values correspond to narrower wind speed distributions, meaning that wind speeds tend to stay within a narrow range and thus the wind turbine would produce a steadier power. We reminder also that the scale parameter C indicates how 'windy' a wind location under consideration.

There are several methods which have been proposed to estimate Weibull parameters [78–80]; graphic method, maximum likelihood method and moment method are commonly used to estimate Weibull parameters. Also, a recent method proposed by Akdag and Dinler [13] in 2009 that is referred to "the power density method" will be exhibited in the following section.

4.2.1. *Moment method*

Justus et al. [81] have proposed the moment method where the shape factor k and scale parameter C can be estimated with the following expressions [82–84]:

$$k = \left(\frac{\sigma}{\overline{V}}\right)^{-1.086} \quad 1 \le k \le 10 \tag{3}$$

$$c = \frac{\overline{V}}{\Gamma(1+(1/k))} \tag{4}$$

where σ, $\overline{V}$, Γ are, respectively, the standard deviation, the mean wind speed and the gamma function.

The standard deviation σ can be calculated as follows:

$$\sigma = \left[\left(\frac{1}{n-1}\sum_{i=1}^{n}(V_i - \overline{V})^2\right)\right]^{0.5} \tag{5}$$

Furthermore, the mean wind speed $\overline{V}$ is calculated by:

$$\overline{V} = \left(\frac{1}{n}\sum_{i=1}^{n} V_i\right) \tag{6}$$

where n is the number of wind speed measurements.

Γ is gamma function which is defined by the following integral equation that can be evaluated by the standard formula [85,86]:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \tag{7}$$

4.2.2. *The cumulative probability method*

This method is derived from the cumulative distribution function which is determined by [51]:

$$F(V_j) = \sum_{i=1}^{j} p(V_i) \tag{8}$$

where $p(V_i)$ is the percentage probability for each winds class which can be given by the following relation:

$$p(V_i) = \frac{f_i}{\sum_{i=1}^{N} f_i} = \frac{f_i}{n} \quad (i = 1,2,\ldots,N) \tag{9}$$

where f_i and n are, respectively, the frequency of each observed speed class and the number of wind speed measurements.

The probability of having all wind speeds will be unity:

$$\int_0^{\infty} p(V)dV = \int_0^{V} p(V)dV + \int_V^{\infty} p(V)dV = 1 \tag{10}$$

In another hand, the above expression can be written as follows:

$$\int_V^{\infty} p(V)dV = 1 - F(V) \tag{11}$$

After integration of $p(V)$ from V to infinity we obtain:

$$1 - F(V) = \exp\left(-\left(\frac{V}{c}\right)^{k}\right) \tag{12}$$

Thus, we achieve the cumulative probability function of a Weibull distribution. In order to write the above relation in a linear from, we take twice logarithm of the cumulative probability function:

$$-\left(\frac{V}{c}\right)^{k} = \ln[1 - F(V)] \tag{13}$$

$$k\ln(V) - k\ln(c) = \ln(-\ln[1 - F(V)]) \tag{14}$$

Now we assume that:

$$x = \ln(V) \text{ and } y = \ln(-\ln[1 - F(V)]) \tag{15}$$

Using this assumption, Eq. (15) will have a linear form: $y = Ax + B$, if $A = k$ and $B = -k\ln(c)$ where $c = \exp(-(B/A))$. Thus, the Weibull parameters are related to the parameters A and B of the line. A is the slope of the straight line and B is its intersection point ordinate with the y-axis. The analytical calculation of A and B is possible using the least squares method (LSQM).

The values of A and B can be found out with the help of the LSQM as follows:

$$A = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{\sum_{i=1}^{N}(x_i - \overline{x})^2} \quad \text{and} \quad B = \overline{y} - A\overline{x} \tag{16}$$

where $\overline{x}$ and $\overline{y}$ are means of x_i and y_i which have to be determined considering the frequency f_i from:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{N} f_i x_i \ \text{ and } \ \overline{y} = \frac{1}{n}\sum_{i=1}^{N} f_i y_i \tag{17}$$

4.2.3. The maximum likelihood method

Stevens and Smulders [87] have suggested the Maximum likelihood method where the shape factor and the scale parameters of the Weibull distribution are estimated by the following two equations:

$$k = \left(\frac{\sum_{i=1}^{n} V_i^k \ln(V_i)}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} \ln(V_i)}{n} \right)^{-1} \tag{18}$$

$$c = \left(\frac{\sum_{i=1}^{n} V_i^k}{n} \right)^{1/k} \tag{19}$$

where V_i and n are, respectively, the wind speed and the number of observed nonzero wind speeds. Using this method, the calculation has two steps such that: (i) calculate the summations in Eqs. (18) and (19) with looking out of zero wind speeds which make logarithm indefinite and at that moment determine the shape parameter with help of Eq. (18) and (ii) find scale parameter using a numerical technique in order to find and calculate the root of Eq. (19) around $k=2$ [13].

4.2.4. Power density method

Akdag and Dinler [13] have developed a new method (2009), namely power density (PD) method, which is very useful to estimate scale and shape parameters thanks to its easy completion, simple formulation and also needs less computation. Indeed, it does not require binning and solving linear least square problem or iterative procedure.

According to the PD method, the shape parameter, K, can be calculated using the following expression:

$$K = 1 + \frac{3.96}{(E_p)^3} \tag{20}$$

where E_p is the energy pattern which according to the literature is between 1.45 and 4.4 for overall wind distribution in the world.

The energy pattern can be expressed also as follows:

$$E_p = \frac{\overline{V^3}}{(\overline{V})^3} \tag{21}$$

where $(\overline{V})^3$and $\overline{V^3}$ are, respectively, the average cube of wind speed and the average of wind speed cubes.

It is noticeable that:

$$(\overline{V}^3) = \left(\frac{1}{n}\sum_{i=1}^{n} V_i \right)^3 \tag{22}$$

$$\overline{V^3} = \frac{1}{n}\sum_{i=1}^{n} V_i^3 \tag{23}$$

where V_i and n are, respectively, the observed wind speed in time stage i and the number of nonzero wind speed data points.

After computing the shape parameter using Eq. (20), the scale parameter can be also calculated easily using the following expression:

$$c = \frac{\overline{V}}{\Gamma(1+1/K)} \tag{24}$$

where $\overline{V}$, Γ are, respectively, the mean wind speed and the gamma function.

4.2.5. Frequency distribution accuracy

In order to control the accuracy of each mentioned Weibull distribution method (M-M: moment method, CP-M: cumulative probability method, ML-M: maximum likelihood method and PD-M: power density method) two examinations are mainly adopted; the first one is the correlation coefficient, R^2, which can be calculated by [13,52]:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - \overline{y})^2} \tag{25}$$

The second one is the root mean square error, RMSE, which is given as follows [49]:

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2 \right]^{0.5} \tag{26}$$

where N, y_i, x_i and $\overline{y}$ are, respectively, the total number of intervals, the frequencies of observed wind speed data, the frequency distribution value calculated with Weibull distribution and the average of y_i values. It is concluded as better method if R^2 magnitude is bigger or RMSE value is smaller.

4.3. Cumulative probability function

The cumulative probability function of the Weibull distribution is given as [88,89]:

$$F(V) = 1 - \exp\left(-\left(\frac{V}{c}\right)^k \right) \tag{27}$$

This function gives the probability of the wind speed exceeding the value u which is expressed by [90]:

$$p(V \geq u) = \exp\left(-\left(\frac{u}{c}\right)^k \right) \tag{28}$$

The probabilities of a wind speed between u_1 and u_2 is given by:

$$p(u_1 < V < u_2) = \exp\left(-\left(\frac{u_1}{c}\right)^k \right) - \exp\left(-\left(\frac{u_2}{c}\right)^k \right) \tag{29}$$

4.4. Most probable and optimum wind speed

There are two meaningful wind speeds for wind energy assessment; the most probable wind speed and the wind speed carrying maximum energy can be simply obtained. The most probable wind speed V_{MP} is referred to the most frequent wind speed for a given wind probability distribution. It can be calculated as the following: [18,22,49]:

$$V_{MP} = c\left(\frac{K-1}{K}\right)^{1/K} \tag{30}$$

The optimum wind speed for a wind turbine maximizing V_{Op} is the speed that generates the most energy. The wind turbine must be selected with a rated wind speed that matches this maximum-energy wind speed for maximizing the generated energy.

This wind speed can be calculated as follows [22,90]:

$$V_{Op} = c\left(\frac{K+2}{K}\right)^{1/K} \quad (31)$$

4.5. Energy and power in the wind

The kinetic energy, E_k, of a mass m of air that moves through a cross section A perpendicular to the wind speed V may be expressed as follows [68]:

$$E_k = \frac{1}{2}mV^2 \quad (32)$$

As the mass of air is the product of the air density ρ and the volume of the air that passes through the area A during the period t. The energy E_k may, therefore, be expressed as follows:

$$E_k = \frac{1}{2}(\rho AVt)\ V^2 = \frac{1}{2}\rho AV^3t \quad (33)$$

It is well known that the power of the wind that flows at speed V through a blade swept area A increases as the cubic of its velocity and is given by [18,20,91]:

$$P(V) = \frac{1}{2}\rho AV^3 \quad (34)$$

The wind power density, $P_d(\rho,V)$, defined as the power per unit of area perpendicular to the direction from which the wind is blowing. $P_d(\rho,V)$ depends on the air density and wind speed. It is given as follows [92–95]:

$$P_d(\rho,V) = \frac{1}{2}\rho V^3 \quad (35)$$

$P_d(\rho,V)$ is the basic unit for measuring the power contained in the wind [33].

Wind power density of a site based on a Weibull probability density function can be expressed as follows [96–100]:

$$\frac{P}{A} = \int_0^\infty P_d(V)f(V)dV = \frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right) \quad (36)$$

Once wind power density of a site is given, the wind energy density for a desired duration T (a month or a year) can be expressed as:

$$\frac{E}{A} = \frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right)T \quad (37)$$

Table 1 recapitulates all wind energy characteristics for a given Weibull distribution:

Table 1
All wind energy characteristics for a given Weibull distribution.

Wind characteristic	Formula
Mean wind speed	$\overline{V} = c \times \Gamma\left(1+\frac{1}{k}\right)$
Standard deviation of wind speed	$\sigma = c \times \sqrt{\left[\Gamma\left(\frac{k+2}{k}\right) - \Gamma^2\left(\frac{k+1}{k}\right)\right]}$
Most probable wind speed	$V_{MP} = c\left(\frac{K-1}{K}\right)^{1/K}$
Optimum wind speed	$V_{Op} = c\left(\frac{K+2}{K}\right)^{1/K}$
Mean wind power density	$\frac{P}{A} = \frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right)$
Mean wind energy density	$\frac{E}{A} = \frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right)T$

5. Outcome results

This section covers the monthly and the yearly diurnal variation of mean wind speed, the annual and the seasonal wind direction, the comparison between the exact wind speed data and the results provided by four Weibull methods in terms of wind frequency distribution. Then, the yearly and the seasonal frequency distribution will be predicted by the most accurate method. Also, the yearly and the seasonal wind "speed-probability duration" of the Tunisian Gulf will be presented. Finally, the exact power density will be fitted by the above-mentioned Weibull methods in order to conclude which method predicts it more truthfully.

5.1. Diurnal mean wind speed and wind direction analysis

5.1.1. Diurnal mean wind speed

The diurnal variation of wind speed gives information about the availability of appropriate winds during the entire 24 h of the day. Thus, to study this pattern, overall hourly mean values of wind speed for every month and for the whole year are shown in Fig. 2.

It is mentioned that the diurnal wind speeds has practically the same shaped trend of variation for all the considered months. It can be found that the daytime, from 7 a.m. to 7 p.m., is windy over all the year, while the night time is relatively calm. Because of thermal convection, the vertical exchange in momentum would be most manifested during early afternoon which, and therefore, results an increase of wind speed. Contrarily, the vertical exchange in momentum is less at night that contributes a decrease of wind speed. The hourly means increase at around 7 a.m. and the peaks are reached at around 4 p.m. After that, the afternoons are characterized by decreasing wind speeds. This point toward that higher electricity could be produced during 7 a.m. to 7 p.m., which also coincide with higher electricity demand time in Tunis. Besides, one can observe that during the summer months a significant rate of variation is occurred which can be explained by the high temperature stratification at the summer period. In fact, as shown from Fig. 2 the highest variation of diurnal mean wind speed is observed during the month of August and it is registered that mean wind speed varied from 3.4 m/s at 7 a.m. to 8.2 m/s at 3 p.m. One can observe also that March, April and May corresponds to the windiest period (spring season) of the whole year with a maximum mean wind speed exceeding the value of 8.66 m/s.

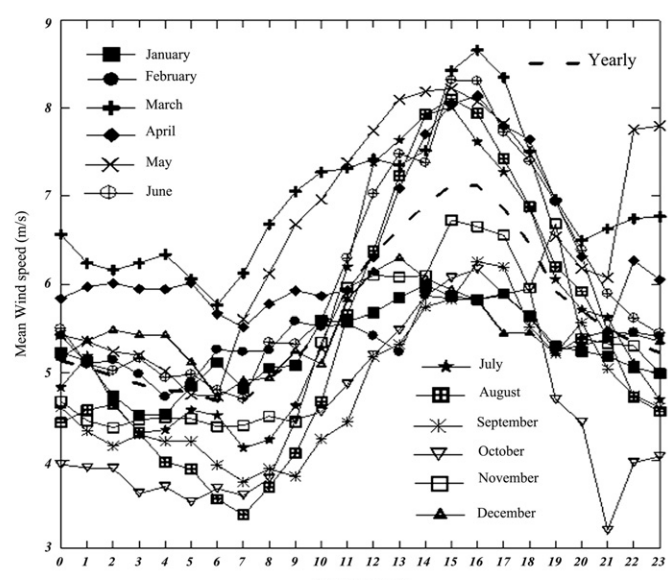

Fig. 2. Yearly and monthly diurnal mean wind speed.

It has to be mentioned that as the accessible data corresponded only to 1 year, no decisive outcomes should be carefully pinched, additional examination should be carried out, since neglecting the diurnal wind patterns could result in significant under- or over-estimation of the wind energy potential of the measurement site.

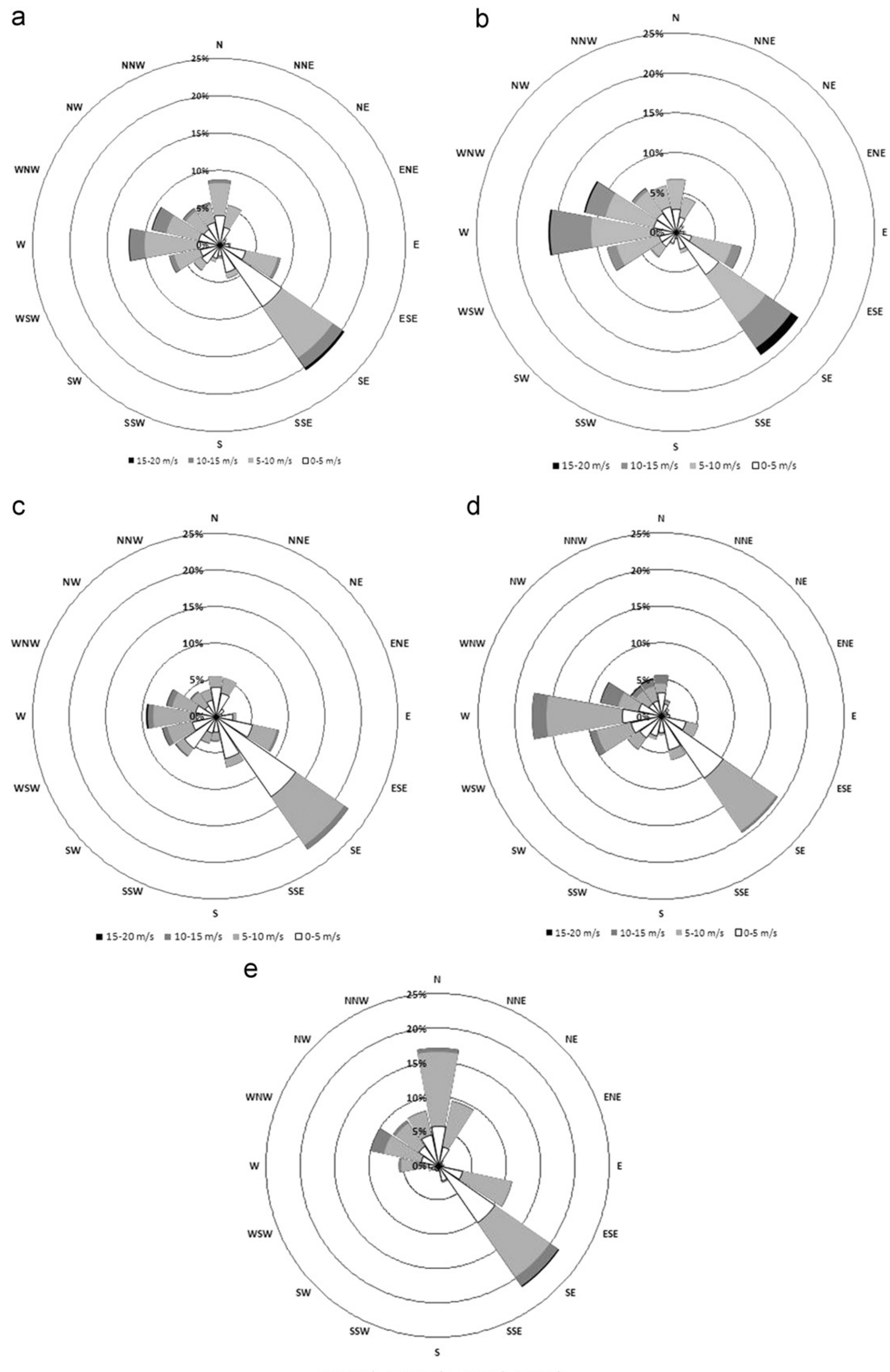

Fig. 3. Annual and seasonal wind roses.

5.1.2. Wind direction analysis

The prediction of wind direction is very imperative when the installation of a wind turbine or a wind farm. For this reason, it has to construct wind roses basing on hourly mean wind speed and corresponding wind direction values. Wind roses differ from one site to another and are identified as form of meteorological fingerprints. Hence, a close look at the wind rose is very useful for sitting wind turbines. So, if a large share of wind comes from a particular direction then the wind turbines should be installed against that direction.

To construct the wind rose and analyze the frequency distribution, all hourly average values of wind speed and wind direction were used, and the obtained wind roses are shown in polar diagrams and are measured clockwise in degrees. The cardinal points (from 0° to 360°) are divided in 16 sectors and each of them covers an arc of 22.5°. The frequencies are plotted in polar diagrams (wind Rose) with respect to the resulted cycle, at 30 m above ground level. Fig. 3(a) shows that the yearly direction of wind blows in the Gulf of Tunis is characterized by its obvious stability. It is noticeable that the most probable wind direction is between 270° and 360°, i.e., southeastern winds. According to the same figure, it is observed that the wind frequency appears to be very low in southwestern, south-southwestern, northeastern and east-northeastern directions. It is remarkable that the widespread winds are southeastern on a contribution of available energy estimated to 20.42%.

One can observe that during the spring season (Fig. 3(b)), the wind prevalent directions are the west and the southeast with a contribution for the producible winds, respectively, by 16.08% and 18.70%. Also, during this season, the mean wind speed did not go over 15 m/s. During the summer season (Fig. 3(c)), the phenomenon of sea breeze, which takes place when temperature differences between the land and the cost increase [33] and therefore a wind from the sea that develops over land near coasts, has a significant impact on the wind direction. It is clear that during this season, the wind flows essentially from the northern and the southeastern directions with a percent of producible wind that exceeds, respectively, 17% and 20%. One can deduce that this phenomenon has an important contribution to the available wind energy in this site. Besides, Fig. 3(c) shows that during the summer season the mean wind speed is always less than 10 m/s and rarely it exceeds this value. During the autumn season Fig. 3(d), the frequencies with which the wind direction falls within each direction sector are very low compared to the other seasons and we conclude that this period corresponds only to the most stable season of the year. The prevalent wind flows from the southeastern direction with a percent equal to 22.16%. Finally, the obtained results during the winter season (Fig. 3(e)) shows that the winds blows from the western and the southeastern directions with a percent, respectively, equal to 17.69% and 19%. It is obvious also that during this season, the probability of high wind speeds are mainly low compared to whose observed during the other seasons.

5.2. Probability density functions

5.2.1. Comparison of methods

Fig. 3 shows the probability density function, or the fraction of time, based on the four above-mentioned methods compared to the exact wind speed data where the wind speed is within the interval given by the width of the columns (here 0.1 m/s is selected). The choice of this bin interpolation is explained by the fact that it shows with precision the probability of a wind speed being in a 0.1 m/s interval centered on a certain value of V. A wind speed frequency histogram is obtained by dividing the number of observations in each bin by the total number of observations in the data set. These actual wind speed observations were fitted in the widely wind energy by Weibull distribution and the suitability of the four well-known distribution will be judged as the first main objective of this paper. The veracity of the Weibull distribution function is mainly assessed according to its ability as how close the predicted probability by Weibull distribution is to the obtained frequency. In this part of this study, air density is considered equal to 1.225 kg/m^3. The correlation

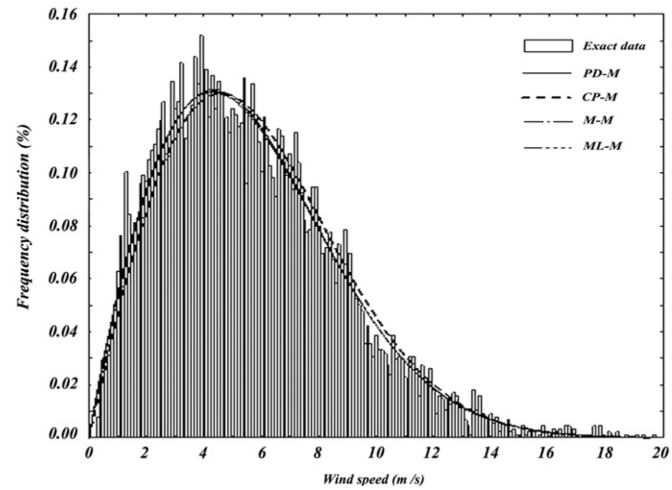

Fig. 4. Comparison between exact wind speed frequency distribution (observed data at 30 m.a.g.l.) with four fitted Weibull PDF based on M-M: moment method, ML-M: maximum likelihood method, CM: cumulative method, PD-M: power density method.

Table 2
Annual comparison of methods at 30 m height.

Parameters	Moment method	MLH method	CP method	PD method
K	1.92474	1.91679	1.97941	1.90083
***c* (m/s)**	6.37011	6.37011	6.55540	6.36771
***R*²**	0.82062	0.82220	0.81176	**0.82489**
RMSE	0.02893	0.02880	0.02964	**0.02859**

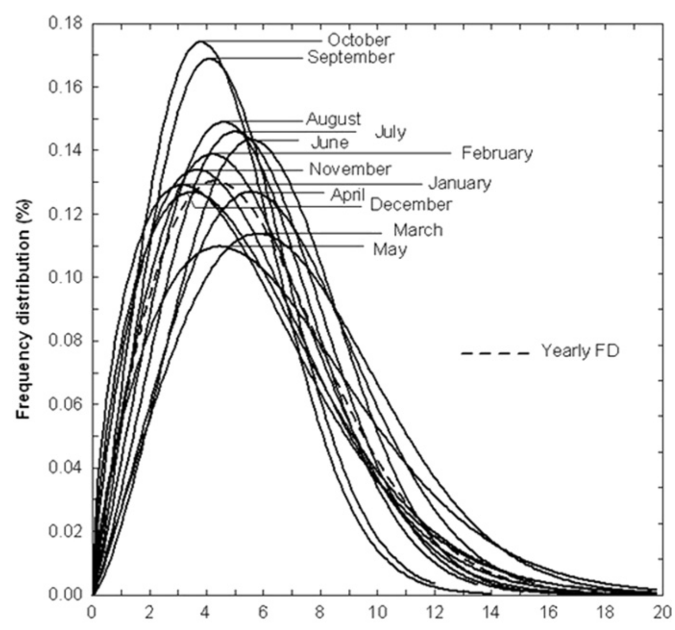

Fig. 5. Monthly frequency distribution.

coefficient (R^2) and the root mean square error (RMSE) are used to evaluate the performance of the four Weibull distributions. As shown in Fig. 4, frequency distributions predicted by the above-mentioned methods fit the exact wind data with good accuracy. Table 2 illustrates the results of the shape factor K, the scale parameter c, the correlation coefficient (R^2) and the root mean square error (RMSE) of each Weibull distribution estimation method. According to the results shown in Fig. 4 and Table 2, Power Density method predicts more accurately the wind speed because it corresponds to the highest value of R^2 and the smallest RMSE value. Thus, it is recommended to predict the wind speed distribution in the central coast of the Gulf of Tunis using the Power Density method. The corresponding values of the yearly shape factor K and scale parameter c are, respectively, 1.90083 and 6.36771.

Table 3
Monthly mean wind speed, Weibull parameters and wind power density at 30 m height.

Month	V_{av} (m/s)	Shape factor (k)	Scale parameter c (m/s)
January	5.27852	1.59035	5.88411
February	5.39119	1.95146	6.08011
March	6.94342	2.11739	7.83990
April	6.43528	2.21942	7.26612
May	6.43490	1.74868	7.22490
June	6.13005	2.43893	6.91283
July	5.69869	2.27507	6.43329
August	5.39888	2.17353	6.09627
September	4.79645	2.19439	5.41593
October	4.54507	2.12456	5.13197
November	5.28341	1.75703	5.93366
December	5.44700	1.65820	6.09377

5.2.2. Frequency distribution analysis

Once the monthly shape factor (k) and scale parameter c are calculated using the power density approach, the estimated annual and monthly Weibull frequency distributions of wind speed of the studied station are shown in Fig. 5 and Table 3. According to the results given by Table 3, it is found that the maximum of average wind speeds are achieved during the months between June and March reaching its highest value of 6.94 m/s in March. Also, the lowest values of mean wind speed are recorded in September and October months reaching its smallest value of 4.54 m/s during the month of October. The results recapitulated in Table 3 show also that the Weibull parameters are dependent on months in a year, which means that the monthly wind speed distribute differently over the whole year. It is clear also that, the shape factor k ranges from 1.59 to 2.43 where it tends to be higher from April to September. The highest c value is 7.83 m/s in March and the lowest is found to be 5.3 m/s in October.

Fig. 5 shows that the peak frequencies are shifted towards the higher values of mean wind speed. The highest peak frequencies are registered during September and October months reaching, respectively, the values of 16.11% and 17.41% while the yearly peak frequency does not exceed the value of 13.50%. We can

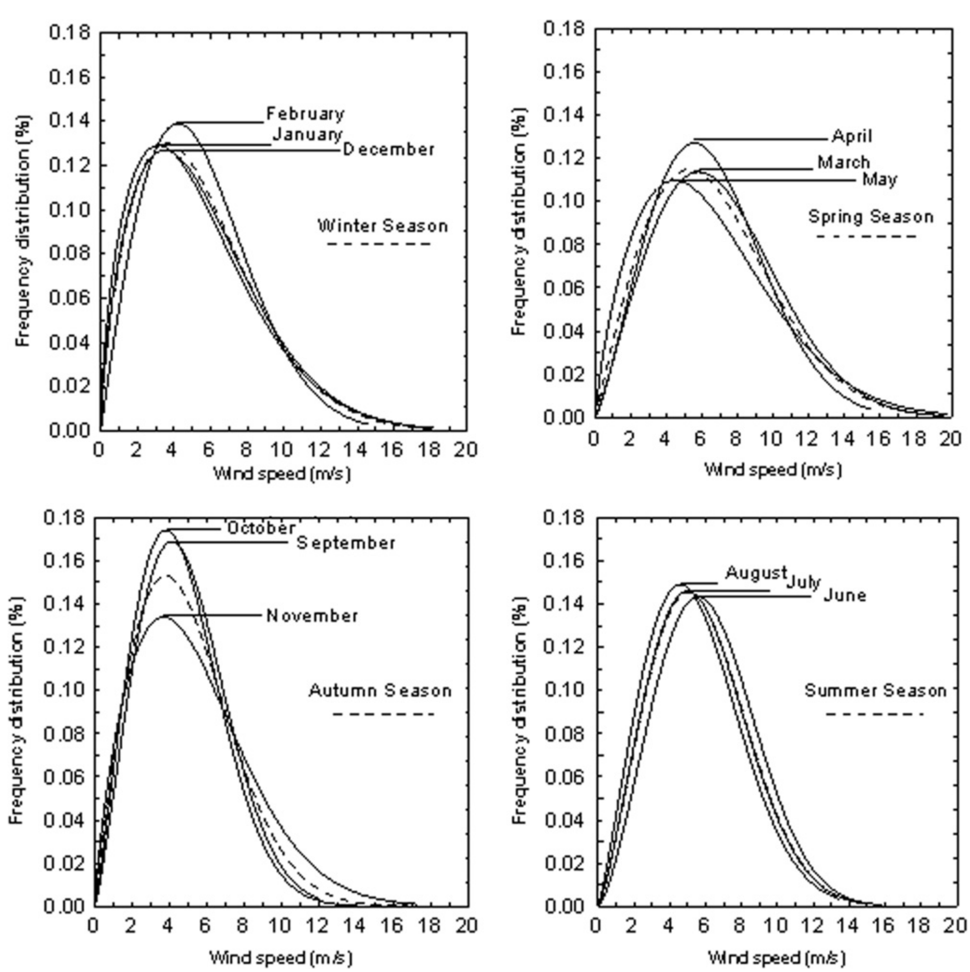

Fig. 6. Seasonal frequency distribution.

observe also the same pattern by comparing the peak of frequency distribution between the yearly one and the lowest values of probability distribution which are related to March and May months. Moreover, the yearly frequency distribution cannot evenly describe well the optimal wind speeds because even it has roughly the same peak of frequency distribution relatively compared to December and April months, the optimal wind speeds of these two months are, respectively, 5.60 and 3.50 m/s while the yearly optimal mean wind speed is 4.03 m/s. Hence, it is clear that the yearly frequency distribution cannot describe accurately the monthly ones in term of peak frequency and optimal wind speed. Therefore, we precede a seasonal frequency distribution analysis to refine better the evaluation of wind frequency distribution.

The seasonal probability distributions of wind speeds are given in Fig. 6. One can observe that the obtained seasonal frequency distribution according to the power density method describes the wind speed distribution in term of peak frequency very well and optimal wind speed along the months in the considered season with the exception of the autumn season. For instance, in winter, spring and summer seasons, the discrepancy in term of peak frequency between the seasonal and the corresponding monthly distributions does not exceed while it can go over 1.8% during the autumn season.

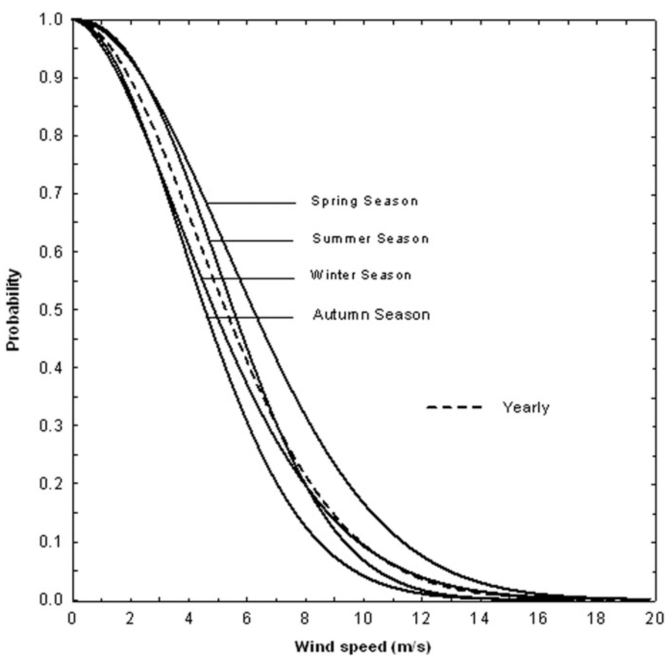

Fig. 7. Yearly and seasonal wind "speed-probability duration" of the Tunisian Gulf.

5.3. Cumulative distribution function

Wind turbines are designed with a cut-in speed, or the wind speed at which it starts to produce power, and a cut-out speed, or the wind speed at which the turbine will be shut down to prevent the drive train from being damaged. For most wind turbines, the range of cut-in wind speed is 3.0–4.5 m/s, so the probability $P(V \geq 3.0)$ and $P(V \geq 4.5)$ are computated as follows:

$$P(V \geq u) = \exp\left(-\left(\frac{u}{c}\right)^k\right) \qquad (38)$$

The probability, which can be expressed also by thousand of operating hours in a year, gives the duration as a function of velocity. It is observed that the operating hours of turbines can reach 6896 h per year (78.72%) if the cut-in speed is 3.0 m/s, and 5224 h (59.63%) if the cut-in speed is 4.5 m/s (assuming the cut-off wind speed is infinite). Hence, the operating ratio is high over the year and the wind power potential in the Golf of Tunis is promising. Fig. 7 shows the seasonal curves "speed-probability" in the studied site at 30 m above ground level. It is noticeable that the four curves have similar changing trend. However, the tendency of decline is higher for autumn and winter seasons than spring and summer seasons. For instance, during the dry period of the year, means both spring and summer seasons, for cut-in speed 3 m/s, the duration of operating hours is about 1877 (85%), while during the wet period (autumn and winter seasons),

Table 4
Yearly, seasonally and monthly most probable and optimum wind speed for different hub heights.

Month	Most probable wind speed (m/s)						Optimum wind speed(m/s)					
	Height (m)						Height (m)					
	10	20	30	40	50	60	10	20	30	40	50	60
January	2.575	2.927	3.155	3.327	3.468	3.587	8.012	9.109	9.818	10.355	10.791	11.161
February	3.433	3.903	4.207	4.437	4.624	4.783	7.122	8.097	8.728	9.205	9.593	9.922
March	4.730	5.378	5.797	6.113	6.371	6.590	8.758	9.957	10.732	11.319	11.796	12.201
April	4.527	5.146	5.547	5.851	6.097	6.306	7.920	9.004	9.705	10.236	10.667	11.033
May	3.629	4.126	4.447	4.691	4.888	5.056	9.118	10.366	11.174	11.784	12.281	12.702
June	4.543	5.165	5.567	5.872	6.119	6.329	7.211	8.198	8.836	9.319	9.712	10.045
July	4.070	4.627	4.987	5.260	5.482	5.670	6.927	7.875	8.488	8.952	9.330	9.650
August	3.746	4.259	4.591	4.842	5.046	5.219	6.716	7.635	8.230	8.680	9.046	9.356
September	3.349	3.808	4.104	4.329	4.511	4.666	5.937	6.750	7.275	7.673	7.997	8.271
October	3.104	3.529	3.804	4.011	4.181	4.324	5.723	6.506	7.012	7.396	7.707	7.972
November	2.998	3.409	3.674	3.875	4.038	4.177	7.462	8.483	9.144	9.644	10.051	10.396
December	2.848	3.238	3.490	3.681	3.836	3.968	8.014	9.110	9.820	10.356	10.793	11.163
Season												
Spring	4.290	4.877	**5.257**	5.545	5.778	5.977	8.617	9.796	**10.559**	11.137	11.606	12.004
Summer	4.107	4.669	5.033	5.308	5.532	5.721	6.963	7.915	8.532	8.998	9.378	9.699
Autumn	3.083	3.505	3.778	3.984	4.152	4.295	6.461	7.345	7.918	8.351	8.702	9.001
Winter	2.935	3.336	3.596	3.793	3.953	4.088	7.735	8.793	9.478	9.996	10.418	10.775
Annual	3.508	3.988	4.299	4.534	4.725	4.887	7.585	8.622	9.294	9.802	10.215	10.566

the operating hours is about 1594 (73%). This is a hopeful result because during the dry period of the year, the wind turbines can operate powerfully and meet the highest electricity demand of Tunis especially corresponding to cooling buildings and even the number of operating hours during the wet period is lesser than these in the dry one; it is promising because heating buildings installations in Tunis has not operating with high electricity background.

5.4. Most probable and optimum wind speed

The maximum and the most probable wind speeds for the different periods during the year at six hub heights are summarized in Table 4. It is found that both the most probable and optimum wind speed increases with height throughout the entire year. It is clear that for all considered ground level heights the lowest values of most probable wind speed are observed in January month while its highest values are achieved during the month of June. Besides, the highest and the lowest values of the most probable wind speed are reached, respectively, during the spring and the winter season. For instance, the most probable wind speed attains the value of 5.257 m/s at 30 m.a.g.l in the spring season while it is slightly more than 3.59 m/s in the winter season. Concerning the maximum wind speeds, its highest and lowest values are registered, respectively, during the months of May and October. One can remark also that the highest values of the maximum wind speed are achieved in the spring season while the smallest ones are reached in the autumn season. For example, the maximum wind speed reaches the value of 10.59 m/s in the spring season at 30 m.a.g.l while it is only about 8.35 m/s in the autumn season.

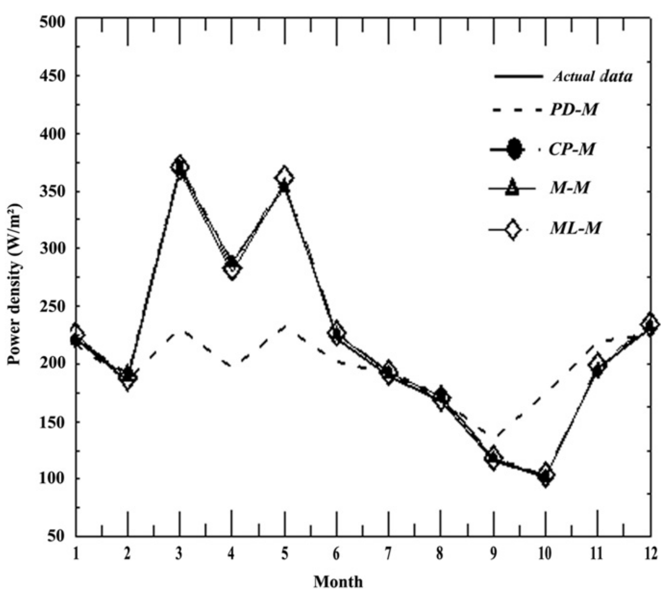

Fig. 8. Comparison between exact wind power density and the four fitted Weibull PDF based on M-M: moment method, ML-M: maximum likelihood method, CM: cumulative method, PD-M: power density method.

5.5. Wind power analysis

As shown in Fig. 8, the highest value of power density is achieved in the month of March reaching 367.04 W/m^2 while the lowest value occur in October reaching 101.86 W/m^2. Table 5 summarizes the comparison of wind power density P_d and average wind speed V_{av} obtained from the actual data and the four methods mentioned previously. It is clear that the moment method (M-M) is the best method for predicting the actual wind power density according to the error P_d with a value of 0.172%. One can deduce also that the cumulative probability method (CP-M) presents the highest value of error with a value of 5.470%. Basing on the results shown in the Table 5, the power density method (PD-M) presents an error P_d of 1.164% and this issue proves that the best method for fitting the frequency distribution of wind speed given by the measurement data does not coincide always with the method which truthfully estimates the wind power density.

6. Conclusion

Detailed statistical study of wind speed and power at 30 m height in the central coast of the Gulf of Tunis in Tunisia is exhibited. Hourly mean wind speeds with a 10-min time step provided by the NRG weather station were statistically analyzed. Wind speeds and power densities are modeled using Weibull probability function whose parameters are identified from four different methods; the moment method, the cumulative probability method, the maximum likelihood method and the power density method. The four probability density functions have been fitted to the measured probability distributions and the power density on a yearly basis (2008–2009). First, based on the results

Table 5
Monthly comparison between average monthly speed and power density calculated using Weibull parameters estimated from the four methods and actual data in the golf of Tunisia at a height of 30 m.

Month	Actual data		Moment method		MLH method		CP method		PD method	
	V_{av} (m/s)	P_d (W/m^2)	V_{av} (m/s)	P_d (W/m^2)	V_{av} (m/s)	P_d (W/m^2)	V_{av} (m/s)	P_d (W/m^2)	V_{av} (m/s)	P_d (W/m^2)
January	5.27852	221.65	5.27852	221.11	5.29495	221.43	5.69902	217.10	5.27852	225.30
February	5.39119	185.49	5.39119	188.79	5.39041	191.34	5.41676	185.48	5.39119	187.94
March	**6.94342**	**367.04**	**6.94342**	**369.22**	**6.94324**	**372.46**	**5.80676**	**230.90**	**6.94342**	**370.70**
April	6.43528	279.41	6.43528	287.61	6.43060	289.15	5.51613	196.37	6.43528	282.98
May	6.43490	357.17	6.43490	352.86	6.45561	353.37	5.81075	231.92	6.43490	361.29
June	6.13005	221.94	6.13005	225.75	6.12243	226.48	5.56611	201.93	6.13005	226.67
July	5.69869	189.42	5.69869	191.97	5.69933	193.04	5.46647	190.92	5.69869	192.43
August	5.39888	167.52	5.39888	171.93	5.69933	172.88	5.25917	169.36	5.39888	170.19
September	4.79645	116.26	4.79645	118.06	4.80078	118.78	4.87385	134.82	4.79645	118.33
October	**4.54507**	**101.86**	**4.54507**	**101.94**	**4.54910**	**102.84**	**5.30730**	**174.33**	**4.54507**	**103.65**
November	5.28341	196.20	5.28341	195.02	5.30424	194.93	5.71610	219.15	5.28341	198.83
December	.44700	230.77	5.44700	231.82	5.46302	233.13	5.76928	225.85	5.44700	234.17
Annual	5.65	219.89	5.65	219.51	5.65	221.46	5.81	231.92	5.65	222.45
Error P_d (%)				**0.172**		0.714		5.470		1.164

given in terms of the correlation coefficient (R^2) and the root mean square error (RMSE) of each Weibull distribution considered in the survey, it is found that the Weibull probability function, with parameters predicted from the power density method (PD-M), estimates the frequency distribution more accurately than the other methods. Second, according to the analysis of the error P_d, it is found that the moment method (M-M) estimates the wind power density more truthfully than the other methods. In this study, the most important characteristics of wind resource have been investigated. The results show that the central coast of Tunis in Tunisia is an important region for exploiting the power of wind electrical energy generation.

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